Sea Level Oscillations and Methodological Implications in Coastal Dynamics Assessments *(Viorel Malciu)*	"Cercetări Marine" Issue no. 43 Pages 148-161	2013

SEA LEVEL OSCILLATIONS AND METHODOLOGICAL IMPLICATIONS IN COASTAL DYNAMICS ASSESSMENTS

Viorel Malciu

NIRDEP - National Institute for Marine Research and Development "Grigore Antipa", 300 Mamaia Blvd., 900581 Constanța, Romania,
E-mail: vmalciu@alpha.rmri.ro

ABSTRACT

This paper aims at establishing the relationship between sea level and changes occurring in the coastal zone as a follow-up of the evolution of this parameter. For the Romanian Black Sea coast, with a specific geomorphological and bathymetric configuration, the influence of sea level manifests differently from one sector to another. As such, these two aspects must be considered when performing coastal dynamics assessments.

On the other hand, although sea level is influenced by the Danube input, it was found that, despite the Danube flow is decreasing, sea level continues to rise. Analyzing the evolution of sea water temperature and air temperature, we found that both parameters show positive growth trends, likely being the cause of the sea level rise and of the flooding of the coastal zone, thus favoring beach erosion.

KEY-WORDS: sea level, geomorphology, Danube input, sea water temperature, air temperature, flooding, beach erosion

AIMS AND BACKGROUND

The coastal zone, defined as the interface between three distinct environments - hydrosphere, atmosphere and lithosphere - has a particular dynamics, generated by the energy transfer between them. Currently, it is estimated that 50% of the population lives on this narrow interface which is the node for a series of economic activities, through the variety of resources it has. Consequently, the rise of sea level, by the loss of land it entails, is a serious issue, which needs to be addressed by appropriate measures, scientifically verified. It is obvious that the coastal zone is the background for two conflicting trends. On the one hand, the increase of greenhouse effect gas emissions causes the increase of air and sea water temperature, leading to the eustatic rise of sea level, which, in its turn, favors beach and cliff erosion, and, on the other hand, the population boom and the increase in the number of tourists enhance the pressure suffered by this sensitive zone.

The sea level rise is the main driver causing the retreat of the shoreline along all sandy beaches worldwide (Bird, 1976). Once the sea level rises, complex issues and phenomena occur. These is a cause-effect relationship between several factors: sea level, sediment input, wave energy and shoreline position. High levels enhance erosion, except for the areas where beach nourishment is excedentary. Growth (transgression) is accompanied by the overall retreat of the shoreline, by erosion or flooding.

MATERIAL AND METHODS

Sea level rise and erosion

The sea level rise causes beach erosion and accelerates the retreat of the shoreline for several reasons (Leatherman, 1991). First of all, high levels enable waves to surge closer to the shore. Secondly, deeper waters close the the shore reduce wave refraction and increase the capacity of longitudinal transport. Finally, high levels allow erosion processes caused by winds and currents to act on the profile, causing its readjustment. The maintenance of a balanced beach profile as a response to sea level rise will cause a movement towards the interior of the beach upwards, in time and space.

There is some confusion in literature on the distinction between erosion and flooding, mainly because they both generate land losses. Erosion is the physical removal of the material making-up the beach or waterfront under the action of waves and currents. The eroded material is either dragged beyond the "closing depth", which is the depth at which the significant movement of sediments is absent, and may be determined by several techniques: grain zise trend analysis, isobath orientation and wave statisctics (Hallermier, 1981). On the contrary, flooding is the permanent covering by water of lowland areas and does not involve any movement of sediments. This way, low beaches are regularly flooded during storms or high water flow periods. The shoreline retreat encompasses the effect of erosion and flooding.

Bruun (1962) is considered to be the first to state the role of sea level rise on coastal erosion. He relied on the balance profile concept - a mean statistical profile in a certain location, which preserves its shape in spite of all its oscillations. However, recent analyses focus on local factors when analyzing erosion, as the input of sea level rise may be masked by local effects (IPCC, 1996).

Bruun's rule is based on an apparently simple bidimensional model of the sediment balance driven towards the shoreline and the offing by sea level oscillations, waves and currents. The beach profile loses its initial balance, migrating towards the interior and upwards, resulting in the erosion of the beach and the adjacent area and deposits in the submerged part of the profile (Fig. 1).

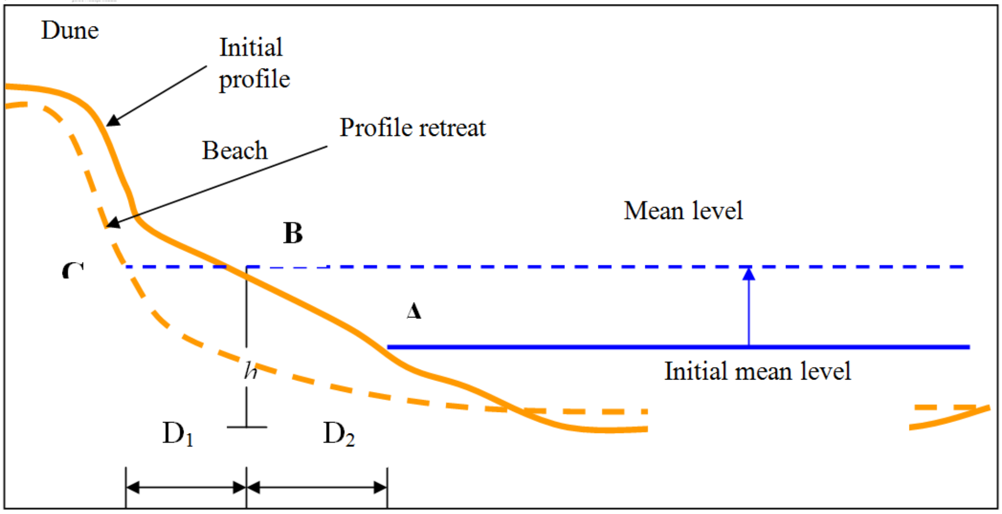

Fig. 1 - Beach profile changes caused by sea level rise

Figure 1 shows the combined effect of erosion and flooding due to sea level rises. D_1 is the shoreline retreat towards the interior due to the mere flooding of the beach, the temporal response being instantaneous. D_2 stands for changes occurring in the profile according to Bruun's rule, which says that, from a balanced profile, the eroded material during shoreline retreat is transferred at the water - land interface and on the inner shelf, thus preserving the original profile of the sea floor. As such, the volume of sand removed from the profile is found in the bathymetric structure of the submerged beach.

Bruun obtained a basic relation for the shoreline retreat limit, R, due to an increase of level, S: R= (L/B + h) S, where L is the distance to the water depth h (closing depth) and B is the height of the sand dune. This type of bidimensional analysis entails the following: 1. The upper beach is eroded due to the inwards translation of the profile; 2. The eroded material from the upper beach is transported and deposited on the submerged beach, thus the eroded volume equals the deposited volume; 3. The increase of nearshore deposits is equal to the level rise and, thus, a constant depth of the water is maintained (SCOR, 1991).

A first conclusion is that Per Bruun's calculations may be considered a preliminary methodology in assessing coastal retreat caused by rising sea level.

Coastal Vulnerability Index - CVI

With the aim of developing the techniques to locate areas of the coastal zone with relative vulnerability at sea level rise, the *Coastal Vulnerability Index - CVI* - is used. It makes a hierarchy of the following areas, in terms of their contribution to shoreline changes caused by sea level rise: geomorphology, coastal zone slope, level rise rate, erosion/accretion rate, effects of tides and waves. Each variable is scaled and they are subsequently combined to obtain an index for certain sectors of the coastal zone. CVI points-out the regions where shoreline changes are likely/possible. This approach combines the natural sensitivity to change of the coastal system with its natural capacity to adapt to environmental condition changes, thus providing a quantitative measure of the natural vulnerability of the system to level rise, using objective criteria. Moreover, it is also necessary to consider additional variables, such as: sediment input in the coastal zone, storms and anthropogenic influences (coastal engineering).

The *Coastal Vulnerability Index* may be a novel method, being an objective assessment tool used to characterize the risks related to sea level rise.

Historical trend analysis

The third method used for forecasting the shoreline position implies the analysis of the historical trend. This type of analysis consists in the empirical determination of past trends and anticipation of the new shoreline position using historical trends. The method is applicable where there are old emplacement plans of constructions built near the coast.

RESULTS AND DISCUSSION

Sea level oscillations at the Romanian Black Sea coast

The systematic recording of sea level began in Romania as early as 1933, by installing a mechanical level recorder, the maregraph (Photo 1). Along with these devices, a hydrometer is also installed, performing visual measurements three times a day, for the apparatus control. The accuracy of measurements, which results in a continuous curve on a gridded paper diagram, is 1 mm.

Photo 1 - The maregraph in the Constanța Harbor and the hydrometer

The data we have since 1933 reveal that the level has an increasing trend, similar to measurements made by other maregraphs in neighboring countries (Table 1).

Table 1 - Sea level trends in Constanța and other Black Sea riparian cities

Location	φ	λ	Years	Time frame	Trend	Standard deviation
Burgas	42º 29'	27º 29'	38	1929-1995	1.55	+/- 0.43
Varna	43º 11'	27º 55'	49	1930-1996	1.36	+/- 0.44
Constanța	44º 10'	28º 40'	57	1933-1996	1.34	+/- 0.51
Sevastopol	44º 37'	33º 32'	82	1910-1994	1.32	+/- 0.28
Tuapse	44º 06'	39º 04'	80	1917-1998	2.14	+/- 0.29

Source: Permanent Service for Sea Level: http://www.pol.ac.uk/psmsl/datainfo/rlr.trend

The sea level oscillations in Constanța throughout the year are influenced by a series of factors, river input being the determining one (Fig. 1).

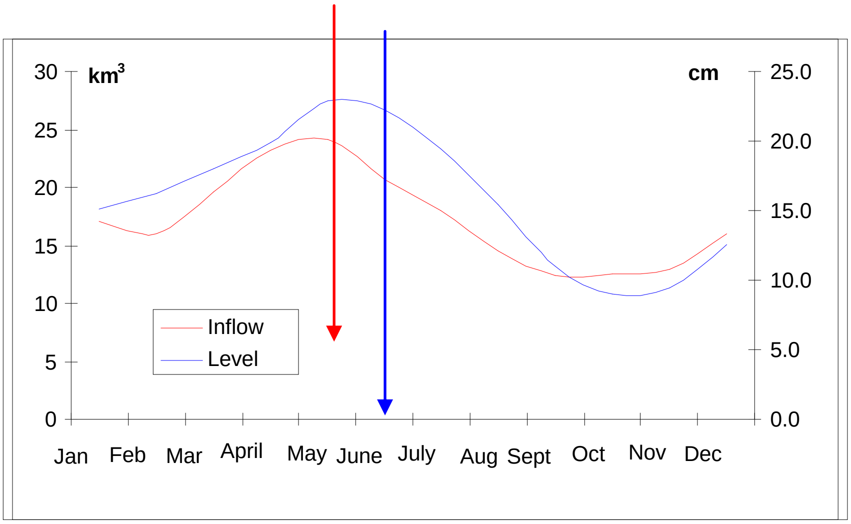

Fig. 1 - Annual evolution of the Danube flow and sea level in Constanța (multiannual monthly means, 1933-2005)

The maximum flow is recorded in May (24.17 km^3), corresponding to the maximum sea level mean, 88 cm. The time offset between the two maxima can be explained by the time required for the flood inrush to reach from the Danube mouths to Constanța.

During the time frame for which we hold data for both parameters, 1959-2005, the annual means show significant oscillations, the level curve following the inflow curve trend.

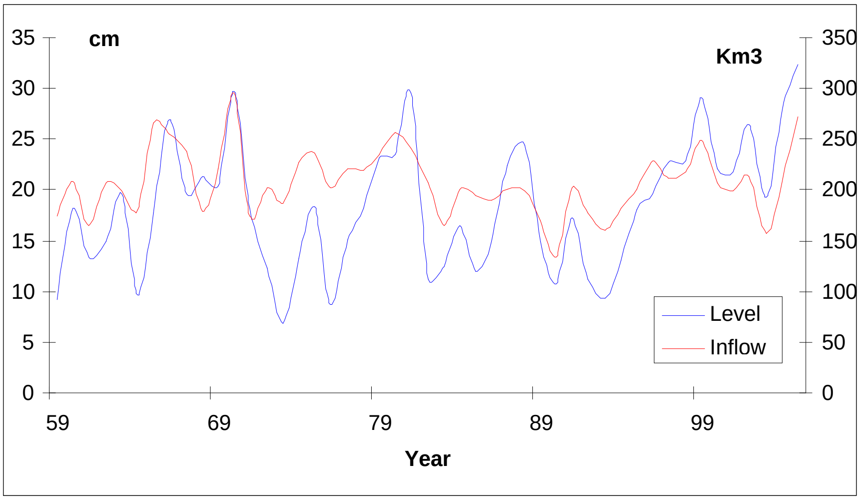

Fig. 2 - Sea level variations in Constanța and Danube inflow in Ceatal Ismail (1959-2005)

Calculating the five year mean (pentads) of annual values and adding the trend for each parameter points-out trends opposite to their evolution. While the Danube inflow shows a decreasing trend, sea level is rising (Fig. 3). As such, even though the sea level is influenced by the Danube inflow, the constant rise is also due to other causes and it can be assumed that one of them is the ice cap meltdown and the global thermal increase.

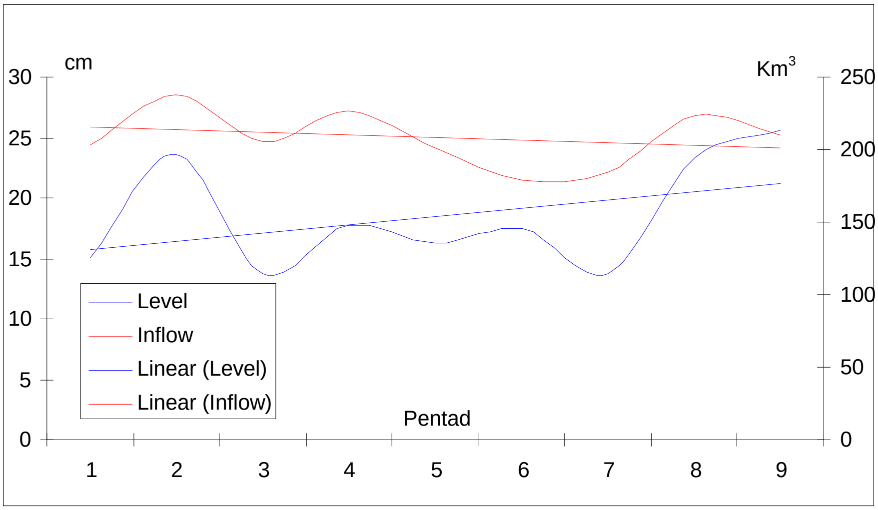

Fig. 3 - Linear trend of the Danube inflow and sea level

The sea level oscillations have different features during certain time frames (Fig. 4).

Period 1962 - 2011

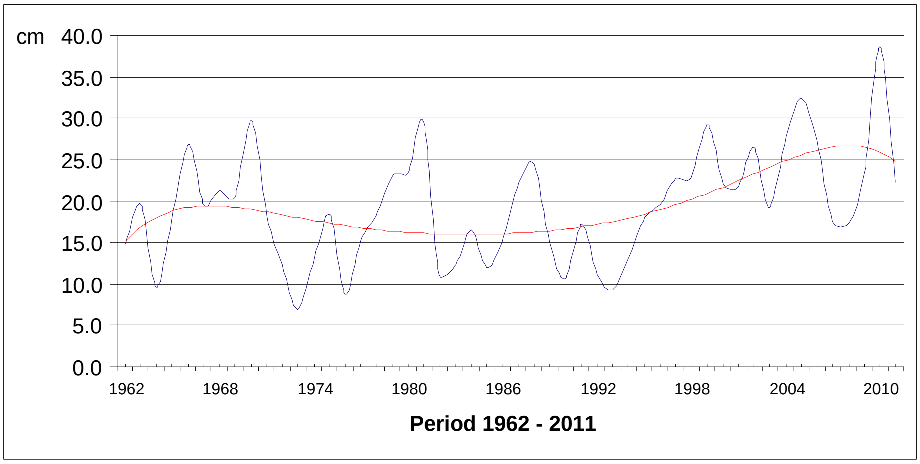

Fig. 4 - Sea level oscillations recorded by the Constanța maregraph during January 1962 - December 2001 (annual means)

Statistical characteristics of the data string:
Mean: 19.3 cm;
Median: 18.8 cm;
Max. 38.7 cm, 2010;
Min. 6.9 cm, 1973;
Range: 31.8 cm;
Standard deviation: 6.8 cm.

Period 2009 - 2012

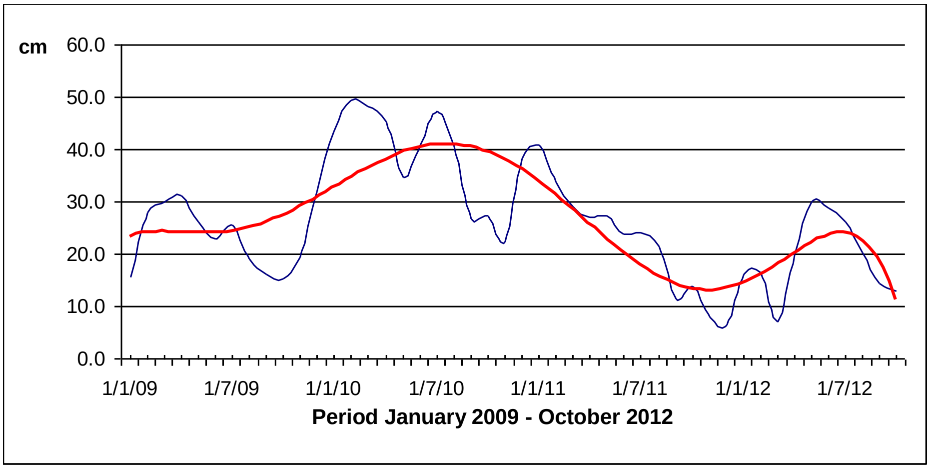

Fig. 5 - Sea level oscillations recorded by the Constanța maregraph during January 2009 - October 2012 (monthly means)

Statistical characteristics of the data string:
Mean: 26.2 cm;
Median: 26.3 cm;
Max. 46.3 cm, Feb. 2010;
Min. 6.5 cm, Dec. 2011;
Range: 39.8 cm;
Standard deviation: 11.2 cm.

Sea level, considered one of the characteristic factors of the marine environment, influences decisively littoral geomorphology and, implicitly, the position of the shoreline and, thus, of the beach area.

According to the analysis of sea level during the past 50 years (Fig. 1), four relatively different periods can be distinguished:

- 1962 - 1967, level rise;
- 1968 - 1985, level drop;
- 1986 - 2007, level rise;
- 2009 - 2012, level drop, however in 2010 the maximum of 38.7 cm was recorded.

The specificity of this whole interval, 1962-2012, is given by the alternance of rise/drop cycles, yet we must underline that the mean of the entire time frame is 2.6 cm above the multiannual mean (1933-2011).

High sea levels cause beach flooding, reducing the beach area, the duration of flooding depending on the existing driving force - local anemobaric regime. At the Romanian coast, the wind regime during the cold season is characterized by northern and north-eastern winds, which leads to increased levels during the whole cold period.

As such, according to the data string analysis in Figure 5 (January 2009 - October 2012), we can distinguish the specific seasonal rises which occur in winter. Actually, the maximum of the interval occurred in February 2010.

We must mention that, during the past period, January - October 2012, the level recorded a minimum of 7.0 cm in March, while in May the maximum was 30.0 cm, after which the level dropped constantly, reaching 12.8 cm in October 2012.

Level persistence in Constanța

The histogram of daily level means during 2001-2005, on 10 cm intervals, reveals the following (Fig. 6).

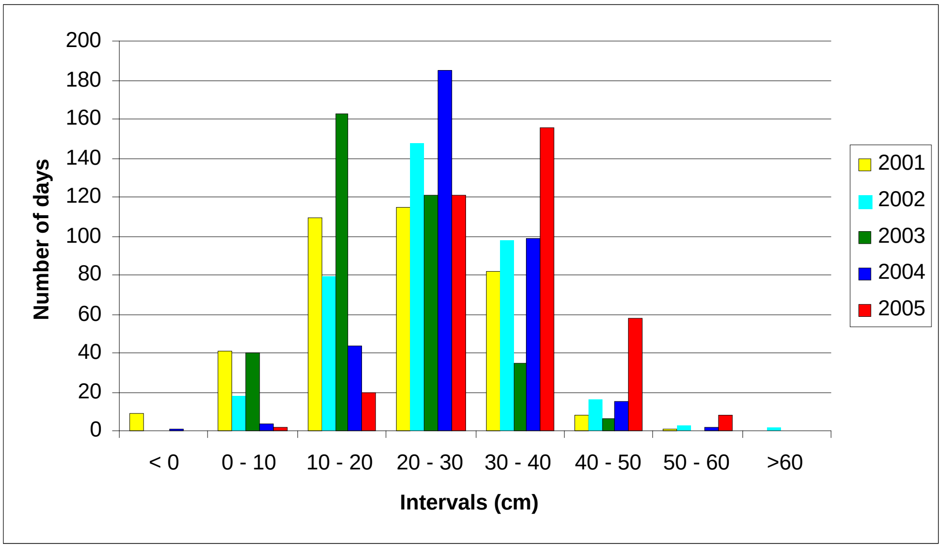

Fig. 6 - Level persistence on daily means during 2001-2005

Of the total 1,809 days of the period 2001-2005, the situation was the following:

< 0 cm	10	days (0.5 %);
0 - 10 cm	105	days (6.0 %);
10 - 20 cm	415	days (23.0 %);
20 - 30 cm	690	days (38.0 %);
30 - 40 cm	470	days (26.0 %);
40 - 50 cm	103	days (5.7 %);
50 - 60 cm	14	days (0.8%);
> 60 cm	2	days -

It is obvious that the dominant interval is 20 - 30 cm, with 690 days, followed by the interval 30 - 40 cm, with 470 days, and 10 - 20 cm, with 415 days. We can conclude that, during a period covering 1,575 days (87%) of the interval analyzed at the Romanian coast, the sea level ranged between 10 cm and 40 cm, with favorable conditions for beach flooding. In 2005, the share shifted to the interval 30 - 40 cm, with 156 days, followed by the intervals 20 - 30 cm, 121 days, and 40 - 50 cm, with 58 days. Summing-up, it results that in 2005, the sea level exceeded 20 cm for 335 days.

Air temperature

Air temperature for the period 1880 - 2004, for the geographical area between 40 - 45º northern latitude and 25 - 30º eastern longitude, shows a positive abnormality of temperature (according to the Global Historical Climatological network dataset) (Fig. 7).

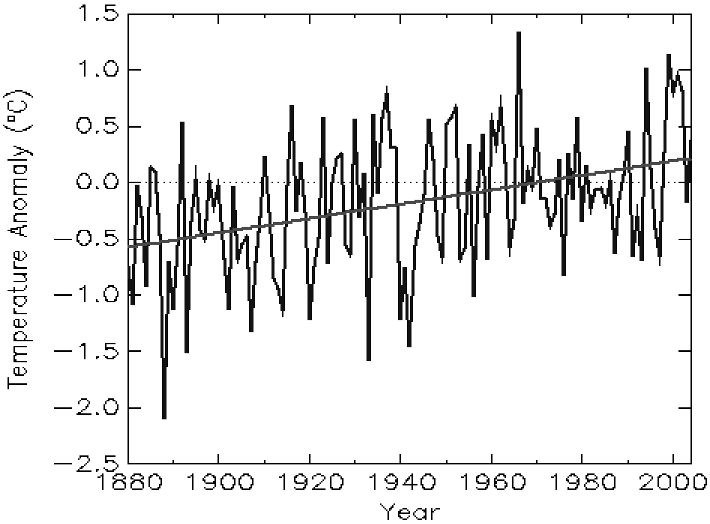

Fig. 7 - Air temperature abnormalities at the Romanian coast

According to measurements performed since 1959, the sea water temperature in Constanța shows an increasing trend, more abrupt during the past decade (Fig. 8).

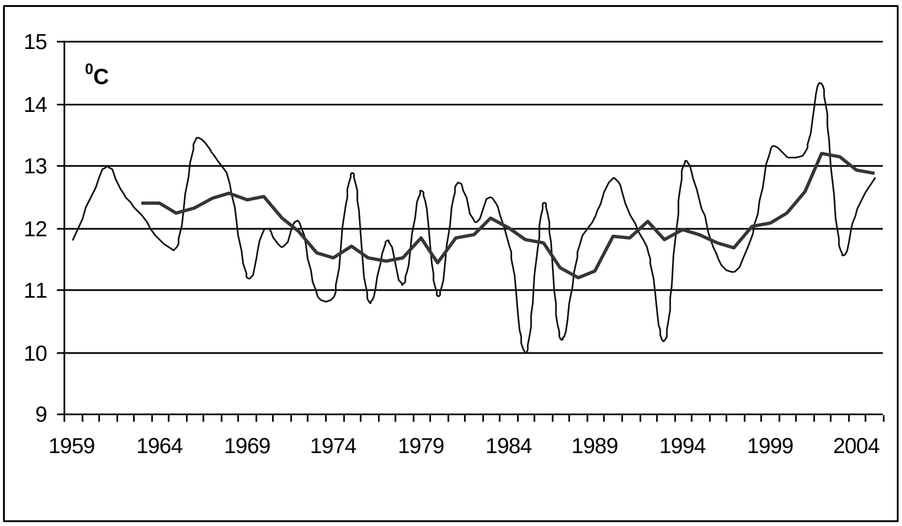

Fig. 8 - Evolution of sea water temperature in Constanța (1959 - 2005)

It must be pointed-out that the multiannual monthly peak of 14.3ºC was recorded in 2002, being by 2.2ºC higher than the multiannual monthly mean.

As a conclusion, at the Romanian coast, both air temperature and sea water temperature show increasing trends, which explains the sea level rise trend as well.

Beach flooding

The sea level rise causes beach flooding, the negative effects being enhanced by the duration of flooding. Thus, in December 1998, at levels close to 50 cm, the Modern Beach was covered by water, the shoreline retreating inwards (Fig. 9 and Photo 1).

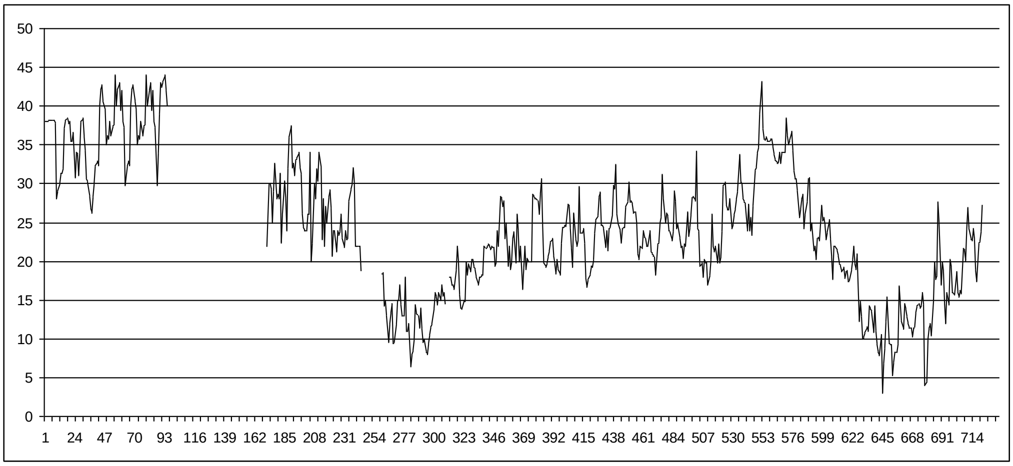

Fig. 9 - Hourly values of sea level in December 1998

CONCLUSIONS

Sea level is the determining factor of shoreline position and it ranged within broad limits, depending on the succession of glaciations which, by storing water in ice caps and icebergs, caused the significant retreat of water. Between glaciations, due to climate warming, ice caps released water to the surrounding ocean. Consequently, in shoreline evolution assessments, sea level is an essential factor. However, it must be mentioned that level variations may differ from one site to another and it is, thus, necessary, to make reference to the closest maregraph. On the other hand, this approach must also be cautious, due to the effects of winds on the sea surface. Wind may act differently during a single day, the values recorded in the northern part of the coast being contrary to the values recorded in the south.

The methodological implications of sea level oscillations in coastal dynamics assessments were identified as follows:

a) Bruun's rule, as preliminary methodology, which states that at a sea level rise of 1 m, erosion is 1 meter;
b) Coastal Vulnerability Index (CVI), which is an operational method for assessing coastal zone vulnerability in relation to level rise;
c) Historical trend assessment.

As such, the need to continue sea level measurements is obvious and it must be made in a systematic manner, in order to delineate the future trends of this parameter, crucial for the coastal zone.

ANNEXES

Photo 1 - Modern Beach, Dec.1998; level + 43.2;
Photo 2 - Modern Beach, July 2005; level +55.7 cm;
Photo 3 - Modern Beach, August 2005; level +36.0 cm;
Photo 4 - Modern Beach, September 2005; level +24.6 cm.

Photo 1 - Modern Beach, December 1998

Photo 2 - Modern Beach, July 2005

Photo 3 - Modern Beach, August 2005

Photo 5 - Modern Beach, September 2005

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